Star Forming Galaxies at $z > 5$

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Abstract. We present recent progress in searching for galaxies at redshift from $z \simeq 5$ to $z \simeq 10$. Wide-field and sensitive surveys with 8m class telescopes have been providing more than several hundreds of star forming galaxies at $z \simeq 5 - 7$ that are probed in the optical window. These galaxies are used to study the early cosmic star formation activity as well as the early structure formation in the universe. Moreover, near infrared deep imaging and spectroscopic surveys have found probable candidates of galaxies from $z \simeq 7$ to $z \simeq 10$. Although these candidates are too faint to be identified unambiguously, we human being are now going to the universe beyond 13 billion light years, close to the epoch of first-generations stars; i.e., Population III stars. We also mention about challenges to find Population III-dominated galaxies in the early universe.

Keywords. galaxies: formation – galaxies: evolution

1. Introduction

Massive stars are key ingredients in the early phase of galaxy formation. First stars (i.e., Population III stars) are considered to be very massive from theoretical aspects although the formation of low mass stars may not be ruled out. Once first massive stars were formed in subgalactic gas clumps within dark matter halos, they could begin to work as cosmic engines because of their huge number of ionizing photons. Then, since they could die after a few million years after their birth, they also supply both kinetic energy and heavy elements even into the intergalactic space. Therefore, massive stars also work as mechanical and chemical engines in the universe. All these issues suggest that the formation and early evolution of galaxies could be controlled by massive stars; how massive, how many massive stars (i.e., more generally, the initial mass function), and when did they begin to form? It is also worthwhile noting that massive stars in the phase of galaxy formation are considered to be related to the cosmic re-ionization of the universe.

In order to investigate these problems, it is necessary to carry out searches for galaxies at very high redshift. Such high-z galaxies have been identified mainly by the following survey methods; (1) optical narrow-band surveys for strong Lyα emitters (LAEs), and (2) optical broad-band surveys for Lyman break galaxies (LBGs) (i.e., the dropout technique; e.g., Steidel *et al.* 1999, 2003; Ouchi *et al.* 2004). Other methods are summarized in Taniguchi *et al.* (2003). Although both methods need follow-up optical spectroscopy to confirm that photometrically selected objects are real high-z galaxies, more than several hundreds of galaxies beyond $z = 5$ have been already found to date thanks to the great observational capability of 8m class telescope facilities (e.g., Dey *et al.* 1998; Rhodes *et al.* 2003; Hu *et al.* 2002, 2004; Ajiki *et al.* 2003; Kodaira et al 2003; Taniguchi *et al.* 2005; Kashikawa *et al.* 2006; Ouchi *et al.* 2008). To probe massive star formation or initial starbursts in early universe, hydrogen Lyα emission provides a powerful tool (Partridge and Peebles 1967; Haiman 2002). Therefore, in this review, we discuss the observational

nature star-forming galaxies at high redshift found mainly by the optical narrow-band imaging surveys made so far (section 2).

In section 3, we give a brief summary of near infrared deep surveys for forming galaxies beyond $z = 7$ and discuss their implication. Another interesting issue is to search for evidence for Population III stars in early universe. Since theoretical consideration suggests that some galaxies at $z \gtrsim 2$ may be dominated by Population III stars because of low feedback from first-generation supernovae. Therefore, in section 4, we give a summary of recent trials for searching for such Population III-dominated galaxies. Finally, in section 5, we discuss future prospects in this research field briefly.

2. Surveys in the Optical Window; Star-forming galaxies at $z = 5 - 7$

When we use the optical window (e.g., 400 nm – 1000 nm), we are able to search for LAEs at $z \sim 2.5$ – 7. If we are interested in LAEs beyond $z = 5$, surveys should be made at wavelengths longer than 700 nm where OH airglow emission lines are bright. Therefore, we have to use some narrow windows where OH airglow is moderately weak; e.g., 815 nm, 920 nm, and so on. These atmospheric windows allow us to search for LAEs at $z \simeq 5.7$ and $z \simeq 6.6$, and so on. A summary of such LAE surveys for $z > 5$ is given in Table 1. We also give a list of the top ten of most distant galaxies found in the optical LAE surveys in Table 2; the most distant LAE known to date is IOK1 at $z = 6.96$ (Iye *et al.* 2006). Note that candidate galaxies around $z \sim 7$ have been found in the GLARE (Gemini Lyman-Alpha at Reionization Era) survey (Stanway *et al.* 2007).

We summarize the observational properties of LAEs at $z = 5 - 7$ as follows. (1) Stellar masses; $\sim 10^{9-10} M_{\odot}$, (2) Sizes (Lyα emission)); a few kpc, (3) Lyα luminosity; $L(\mathrm{Ly}\alpha)$ $\sim 10^{42-43}$ erg s^{-1}; (4) Stellar ages; several million to several hundreds million years; (5) Star formation rates; a few to several tens $M_{\odot}$ yr^{-1}; (6) Star formation rate densities; $\sim 10^{-3}$ $M_{\odot}$ yr^{-1} Mpc^{-3}; (7) Morphology (Lyα emission); spatially extended, but only few information; and (8) Morphology (UV continuum); spatially extended (smaller than Lyα emission), but only few information (e.g., Rhoads *et al.* 2005; Taniguchi *et al.* 2008).

Note, however, that more massive galaxies tend to be found in high-z LBG samples with stellar masses of $\sim 10^{10-11} M_{\odot}$ (e.g., Egami et al. 2005; Mobasher *et al.* 2005; Yan *et al.* 2006; Eyles *et al.* 2007 and references therein). Moreover, the star formation rate densities for high-z LBGs is $\sim 10^{-2}$ $M_{\odot}$ yr^{-1} Mpc^{-3}, being higher by one order of magnitude than those of LAEs at similar redshifts (e.g., Taniguchi *et al.* 2005 and references therein).

The Lyα luminosity function for LAEs at $z > 5$ has been obtained for several samples of LAEs (e.g., Ajiki *et al.* 2004; Hu *et al.* 2004; Shimasaku *et al.* 2006; Kashikawa *et al.* 2006). One interesting point is that bright LAEs appear to be rarer at $z \approx 6.5$ than at $z \approx 5.7$ in the Subaru Deep Field (Kashikawa *et al.* 2006), suggesting a possible evolutionary effect from $z \approx 6.5$ to $z \approx 5.7$.

As for large-scale structures in early universe, there are lines of evidence for galaxy clustering below $z \approx 6$ [at $z \approx 5.7$ (Hu *et al.* 2004; Ouchi *et al.* 2005), and at $z \approx 4.9$ (Shimasaku *et al.* 2003)] although there is no strong evidence for such clustering at $z \approx 5.7$ (Ajiki *et al.* 2003; Murayama *et al.* 2007). Beyond $z = 6$, no such clustering feature has been found to date (Kashikawa *et al.* 2006). These observations suggest that the large-scale structure probed by LAEs could grow up from $z \sim 6$.

Table 1. Top ten of high-redshift galaxies found in the optical surveys

Window (nm)	Field	z	V (Mpc^3)	N(photo)	N(sp)	Ref.
973	SDF	6.96	3.2×10^5	2	1	a
921	SDF	$6.5 - 6.6$	3.2×10^5	58	34	b, c, d
912	6 fields	6.56	–	1	1	e
816	SDSS1044	5.7	2.0×10^5	20	2	f
815, 823	LALA	$5.7 - 5.8$	$\sim 2 \times 10^5$	18	2	g
816	SSA22	5.7	1.9×10^5	26	19	h
816	SDF	5.7	1.9×10^5	89	37	i
816	GOODS-N	5.7	4.0×10^4	10	–	j
816	GOODS-S	5.7	4.0×10^4	4	–	j
816	COSMOS	5.7	1.8×10^6	119	–	k
816	SXDS	5.7	9.2×10^5	401	17	l

Field: SDF = Subaru Deep Field (Kashikawa *et al.* 2004), SDSS1044 = SDSSp J104433.04-012522.2 (Fan *et al.* 2000), LALA = Large Area Lyman Alpha survey, SSA22 = Small Selected Area at RA = 22h, GOODS = Great Observatory Origins Deep Survey - North and South (Giavalisco *et al.* 2004), COSMOS = Cosmic Evolution Survey (Scoville *et al.* 2007), and SXDS = Subaru XMM-Newton Deep Survey (Sekiguchi *et al.* 2004)
Survey Volume (V): A flat universe with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1} is adopted.
N(photo): The number of LAEs identified by photometric conditions.
N(sp): The number of LAEs confirmed by follow-up spectroscopy. Note that follow-up spectroscopy is going on in some cases.
References: a = Iye *et al.* 2006, Ota *et al.* 2008; b = Kodaira *et al.* 2003; c = Taniguchi *et al.* 2005; d = Kashikawa *et al.* 2006; e = Hu *et al.* 2002; f = Ajiki *et al.* 2003 (see also Ajiki *et al.* 2004); g = Rhodes & Malhotra 2001, 2003; h = Hu *et al.* 2004; i = Shimasaku *et al.* 2005; j =Ajiki *et al.* 2006; k = Murayama *et al.* 2007; l = Ouchi *et al.* 2008

Table 2. Top ten of high-redshift galaxies found in the optical surveys

No.	Name	Redshift	Ref.
1	IOK1	6.96	a
2	SDF132522.3+273520	6.597	b
3	SDF132520.4+273459	6.596	c
4	SDF132357.1+272446	6.589	c
5	SDF132432.5+271647	6.580	b
6	SDF132528.8+273043	6.578	b
6	SDF132418.3+271455	6.578	b, d
8	HCM-6A	6.56	e
9	SDF132432.9+273124	6.557	c
10	SDF132408.3+271543	6.554	b

References: a = Iye *et al.* 2006, Ota *et al.* 2008; b = Taniguchi *et al.* 2005; c = Kashikawa *et al.* 2006; d = Kodaira *et al.* 2003; e = Hu *et al.* 2002

3. Surveys in the Near-Infrared Window; Star-forming galaxies at $z > 7$

The success of optical searches for high-z galaxies up to $z \approx 7$ urged us to carry out near-infrared (NIR) surveys for very high-z galaxies beyond $z = 7$. Such galaxies, if any, could be much fainter than galaxies with $z < 7$ because they could be in still in a mass assembly phase in their evolution. Moreover, the attenuation of H I atoms should be much severe for detecting Lyα emission although cosmological H II regions around LAEs could help for such detection (e.g., Haiman 2002). In this section, we give a summary of recent NIR surveys for forming galaxies.

[1] *Narrow-band Imaging Surveys*: The narrow-band imaging technique provides us a large number of LAEs at $2 < z < 7$. Therefore, this technique should be applied in the NIR window.

The first NIR trial was reported by Willis & Courbin (2005). Their project name is "ZEN (z equal nine)". They used a narrowband filter centered at 1.187 μm in J band with VLT/ISAAC (FOV = 2.5 arcmin × 2.5 arcmin). They found no LAE candidate with $L(\mathrm{Ly}\alpha) > 10^{43}~h^{-2}$ erg s^{-1} in the survey volume of 340 h^{-3} Mpc^{-3} where $h = H_0/100$. They also made a similar deep NIR narrowband imaging survey for LAEs in three lensing cluster areas (Abell 114, 1689, and 1835). Again, they found no LAE candidate with $L(\mathrm{Ly}\alpha) > 10^{43}~h^{-2}$ erg s^{-1} in the survey volume of 1270 h^{-3} Mpc^{-3}.

Using the same instrument and the NIR narrowband filter used in the ZEN survey, Cuby *et al.* (2007) made a survey for LAEs at $z \approx 9$ in seven fields, covering 31 arcmin^2 in total. Although their survey area is wider than that of ZEN, they found no LAE candidate.

[2] *Broad-band Imaging Surveys*: The broad-band imaging technique is also powerful to detect high-z galaxies. This is the same technique as the Lyman break method in the optical. The deepest NIR imaging survey data are provided by the Hubble Ultra Deep Field (Bouwens *et al.* 2005; see also Bouwens & Illingworth 2006). The survey depth is down to 28.6 in J_{110}(AB) and 28.5 in H_{160}(AB) with a 0.6 arcsec aperture. They found three probable galaxies at $z \sim 10$ with $H_{160} \simeq 28$, corresponding to $\approx 0.3L^*_{z=3}$. Unfortunately, all these sources are too faint to be observed in spectroscopy. The presence of these objects gives a star formation rate density of $\sim 10^{-3}$ M$_\odot$ yr^{-1} Mpc^{-3}, being smaller by one order of magnitude than that at $z = 5 - 6$.

When we use ground-based telescopes, the survey depth is around 25 AB magnitude in J and H at best because of strong airglow emission. Therefore, NIR broadband imaging surveys for a blank field from the ground may not work well. Or, we need help of gravitational lensing. Richard *et al.* (2006) made deep NIR imaging survey for two lensing cluster regions (Abell 1835 and AC 114) by using VLT/ISAAC. Their survey depth is 25.5 – 25.6in J(AB), 24.7 in H(AB), and 24.3 – 24.7 in K_s(AB) for the two regions. They found 8 and 5 probable candidates at $7 < z < 10$ in Abell 1835 and AC 114, respectively. Given the magnification factor from 1.5 to 10, their star formation rate ranges from a few to 20 M$_\odot$ yr^{-1}.

[3] *Blind Spectroscopic Surveys along Caustic Lines*: This technique is very unique but very powerful in finding intrinsically faint objects at high redshift; see for optical trials, Ellis *et al.* (2001) and Santos *et al.* (2004). Stark *et al.* (2007) made NIR spectroscopic surveys for gravitationally-lensed LAEs around nine intermediate-z clusters of galaxies by using Keck/NIRSPEC. Since their spectroscopic survey is designed to sweep the caustic lines of the gravitational lensing, the amplification factor is as high as $10 - 50$ for objects around $z = 10$. They found 6 probable LAE candidates at $z = 8.7 - 10.2$. Among them, two objects are the most likely candidates from their careful follow-up observations; Abell 68 c1 at $z = 9.32$ and Abell 2219 c1 at $z = 8.99$.

We have introduced five independent deep NIR surveys for high-z galaxies beyond $z = 7$. Generally speaking, it is more difficult to find candidates of forming galaxies in NIR than in optical. One reason is that there is no very wide-field NIR imager on 8m class telescopes. MOIRCS on the Subaru Telescope has FOV = 4 arcmin × 7 arcmin (http://www.subarutelescope.org/Observing/Instruments/MOIRCS/index.html) and HAWK-I on VLT has FOV = 7 arcmin × 7 arcmin (http://www.eso.org/instruments/hawki/).

Although these NIR cameras have widest FOV on such 8m class telescopes, their FOVs are still much smaller than those of optical cameras (> 30 arcmin $\times$ 30 arcmin). Note that both the stronger airglow emission and the much severe Tolman dimming [i.e., the surface brightness dimming as $(1 + z)^{-4}$] also makes it difficult to detect LAEs at NIR. Also, forming galaxies at $z > 7$ could be faint intrinsically.

4. Surveys for Population III–dominated Galaxies

One interesting issue is to address on first stars in our universe: When were they made? How massive were they? How did they affect the nature of intergalactic medium, chemically and dynamically? Did only first stars contribute to the cosmic re-ionization? How were they related to the formation of supermassive black holes? In order to give firm answers to these questions, it is necessary to probe first stars or forming galaxies at very high redshift.

The major epoch of Pop III star formation may be at $z \sim 10 - 30$, when dark matter halos with mass of $M_{\mathrm{halo}} \sim 10^6$ M$_\odot$ could have grown up to form first stars (see for a review, Loeb & Barkana 2001). Shortly after the formation of Pop III stars ($\sim 10^6$ years after), first supernova explosions could occur and then pollute the gas inside and outside of dark matter halos. However, if this feedback process is inefficient, Pop III stars could be born in galaxies even at $z \sim 2$ or so (e.g., Scannapieco *et al.* 2003; Schneider *et al.* 2006; Jimenez & Haiman 2006; Tornatore *et al.* 2007; see also, for recent review, Norman 2008). If this is the case, it is possible to probe Pop III dominated forming galaxies in the optical window.

There are two important observational properties of such Pop III dominated galaxies. One is the large equivalent width (EW) of hydrogen Lyα emission. The other property is moderately strong He II λ1640 emission. These properties are attributed to the very high effective temperature ($\sim 10^5$ K) of Pop III stars (e.g., Tumlinson & Shull 2000; Tumlinson *et al.* 2001, 2003; Bromm *et al.* 2001; Oh *et al.* 2001; Schaerer 2002, 2003). Interestingly, it has been reported that some high-z LAEs have a large rest-frame equivalent width of Lyα emission with $EW_0 > $ a few 100 Å (e.g., Malhotra & Rhoads 2002; Nagao *et al.* 2004, 2005a, 2007; Shimasaku *et al.* 2006; Dijkstra & Wyithe 2007). These observations may not be explained with photoionization by usual massive stars.

For one of such LAEs with a large EW Lyα emission, Nagao *et al.* (2005a) made an ultra deep NIR spectroscopy to detect He II emission; SDF 132440.6+273607 with $EW_0(\mathrm{Ly}\alpha) = 130$ Å and $L(\mathrm{Ly}\alpha) = 1.8 \times 10^{43}$ erg s^{-1} at $z = 6.33$. However, they found no He II feature, suggesting $L(\mathrm{HeII}) < 1.4 \times 10^{42}$ erg s^{-1}. Stacking analyses of spectra of high-z galaxies also found no evidence for Pop III-driven He II emission; (1) Shapley *et al.* (2003) examined the stacked spectrum of $\simeq 1000$ LBGs at $z \simeq 3$ and obtained evidence for He II emission. However, the authors suggested that this feature may be attributed to Pop I hot stars such as WR stars (see also the comment given by Max Pettini in the discussion; cf. Jimenez & Haiman 2006). (2) Ouchi *et al.* (2008) examined the stacked spectrum of $\simeq 50$ LBGs at $z = 3.7$ and found no He II emission. (3) See the comment given by Jon Eldridge in discussion.

Recently, Nagao *et al.* (2008) made a unique survey for Lyα-He II emitters by using combination of intermediate- and narrow-band filters in the optical window. They used (i) IA598 and NB816 filters for LAEs at $z \approx 4.0$ and (ii) IA 679 and NB921 for LAEs at $z \approx 4.6$, where the Subaru IA filter system consists of 20 filters covering from 4000 Å to 9500 Å with a spectroscopic resolution of $R = \lambda/\Delta\lambda = 23$ (Taniguchi 2001; see also Ajiki *et al.* 2004; Yamada *et al.* 2005). Their survey field is SDF. Although they found 10 dual-line emitters, they are not identified as Lyα/He II emitters (i.e., low-z dual-line

emitters such as [O II]/[O III] ones. Their survey shows that there is no LAEs with Pop III star formation rate with $> 2M_\odot$ yr^{-1} and the Pop III star formation rate density is lower than $5 \times 10^{-6}M_\odot$ yr^{-1} Mpc^{-3}, being smaller by a few orders of magnitudes than those of LAEs at similar redshifts.

5. Future Prospects

Finally, we give comments on future prospects. As shown in previous sections, optical deep surveys have been finding a large number of forming galaxies at $z \sim 5 - 7$. However, NIR deep surveys have been facing to the technical limit of the existing large telescope facilities including the Hubble Space Telescope. Therefore, we will have to wait for next-generation telescopes in order to improve our knowledge on massive stars at very high redshift (i.e., Pop III stars) and star formation history of in very young galaxies.

We will have two types of new-generation telescopes in near future; one is the James Webb Space Telescope (JWST: Sonneborn, this volume; see http://www.jwst.nasa.gov/) and the other is extreme large telescopes (ELTs) on the ground such as the European-ELT (D'Odorico, this volume; see http://www.eso.org/sci/facilities/eelt/) and the Thirty Meter Telescope (TMT: http://www.tmt.org/) led by Caltech and University of California. Extremely high observational capabilities of these telescopes will open the door to Pop III dominated universe. In particular, mid infrared observations with JWST will be able to go to $z \sim 30$.

Yet, we will have to do our best to find much younger, Pop III-dominated galaxies at high redshift up to $z \sim 30$ before next-generation, space and ground-based telescopes will come. For this effort, we have two nice helpers. One is the gravitational lensing, as demonstrated in section 3 (e.g., Stark *et al.* 2007; Richard *et al.* 2006). The other helper is very bright gamma-ray bursts at high redshift. After the gamma ray bursts (GRBs), very bright optical flashes have been often observed. The most distant GRB event known to date was found at $z = 6.33$ (Kawai *et al.* 2006). If such GRB events will occur at $z \sim 7$, we will be detect their rest-frame optical flashes in the NIR windows (see Fynbo, this volume).

As for the formation and evolution of galaxies, next-generation telescopes will allow us to explore what happened in galaxy formation and in early evolution phase. Then, we will be able to obtain a unified picture for various types of galaxies at high redshift, e.g., LAEs, LBGs, EROs (extremely red objects), DRGs (distant red galaxies), BzKs (galaxies selected from BzK photometry), SMGs (submillimeter galaxies), and so on. Finally, we will learn how massive stars have been working as cosmic engines for more than 10 billion years.

Acknowledgements

References

Ajiki, M., Taniguchi, Y., Fujita, S. S., *et al.* 2003, *AJ*, 126, 2091
Ajiki, M., Taniguchi, Y., Fujita, S. S., *et al.* 2004, *PASJ*, 56, 597
Ajiki, M., Mobasher, B., Taniguchi, Y., *et al.* 2006, *ApJ*, 638, 596
Bouwens, R. J., Illingworth, G. D., Thompson, R. I., & Franx, M. 2005 *ApJ*, 624, L5
Bouwens, R. J. & Illingworth, G. D. 2006 *Nature*, 443, 189

Bromm, V., Kudritzki, R. P., & Loeb, A. 2001, *ApJ*, 552, 464

Cuby, J. G., Hibon, P., Le Febre, O., *et al.* 2007, *A&A*, 461, 911

Dey, A., Spinrad, H., Stern, D., *et al.* 1998, *ApJ*, 498, L93

Dijkstra, M. & Wyithe, J. S. B. 2006, *MNRAS*, 379, 1589

Egami, E., Kneib, J.-P., Rieke, G. H., *et al.* 2005, *ApJ*, 618, L5

Ellis, R. S., Santos, M. R., Kneib, J. -P., & Kuijken, K. 2001, *ApJ*, 560, L119

Eyles, L. P., Bunker, A. J., Ellis, R. S., *et al.* 2008, *MNRAS*, 374, 910

Fan, X., White, R. L., Davis, M., *et al.* 2000, *AJ*, 120, 1167

Giavalisco, M., Dickinson, M., Ferguson, H. C., *et al.* 2004, *ApJ*, 600, L93

Haiman, Z. 2002, *ApJ*, 576, L1

Hu, E. M., Cowie, L. L., McMahon, R. G., *et al.* 2002, *ApJ*, 568, L75 (Erratum, 576, L99)

Hu, E. M., Cowie, L. L., Capak, P., *et al.* 2004, *AJ*, 127, 563

Jimenez, R. & Haiman, Z. 2006, *Nature*, 441, 120

Kashikawa, N., Shimasaku, K., Yasuda, N., *et al.* 2004, *PASJ*, 56, 1011

Kashikawa, N., Shimasaku, K., Malkan, M. A., *et al.* 2006, *ApJ*, 648, 7

Kawai, N., Kogugi, G., Aoki, K., *et al.* 2006, *Nature*, 440, 184

Kodaira, K., Taniguchi, Y. Kashikawa, N., *et al.* 2003, *PASJ*, 55, L17

Loeb, A. & Barkana, R. 2001, *ARA&A*, 39, 19

Malhotra, S. & Rhoads, J. E. 2002, *ApJ*, 565, L71

Mobasher, B., Dickinson, M., Ferguson, H. C., *et al.* 2005, *ApJ*, 635, 832

Murayama, T., Taniguchi, Y., Scoville, N. Z., *et al.* 2007, *ApJS*, 172, 523

Nagao, T., Taniguchi, Y., Kashikawa, N., *et al.* 2004, *ApJ*, 613, L9

Nagao, T., Kashikawa, N., Malkan, M. A., *et al.* 2005a, *ApJ*, 634, 142

Nagao, T., Motohara, K., Maiolino, R., *et al.* 2005b, *ApJ*, 631, L5

Nagao, T., Murayama, T., Maiolino, R., *et al.* 2007, *A&A*, 468, 877

Nagao, T., Sasaki, S., Maiolino, R., *et al.* 2008, *ApJ*, in press (arXiv:0802.4123)

Norman, M. L. 2008, in: B. W. O'Shea, A. Heger & T. Abel (eds.), *First Stars III* (New York: AIP), *AIP Conference Ser* in press (arXiv:0801.4924)

Oh, S. P., Haiman, Z., & Rees, M. J. 2001, *ApJ*, 553, 73

Ota, K., Iye, M., Kashikawa, N., *et al.* 2008, *ApJ*, submitted (arXiv.0707.1561)

Ouchi, M., Shimasaku, K., Okamura, S., *et al.* 2004, *ApJ*, 611, 660

Ouchi, M., Shimasaku, K., Akiyama, M., *et al.* 2005, *ApJ*, 620, L1

Ouchi, M., Shimasaku, K., Akiyama, M., *et al.* 2008, *ApJS*, in press (arXiv:0707.3161)

Partridge, R. B. & Peebles, P. J. E. 1967, *ApJ*, 147, 868

Rhoads, J. E. & Malhotra, S. 2001, *ApJ*, 563, L5

Rhoads, J. E., Malhotra, S., Dey, A., *et al.* 2000, *ApJ*, 545, L85

Rhoads, J. E., Dey, A., Malhotra, S., *et al.* 2003, *AJ*, 125, 1006

Rhoads, J. E., Panagia, N., Windhorst, R. A., *et al.* 2005, *ApJ*, 621, 582

Richard, J., Pello, R., Schaerer, D., *et al.* 2006, *A&A*, 456, 861

Santos, M. R., Ellis, R. S., Kneib, J. -P., *et al.* 2004, *ApJ*, 606, 683

Scannapieco, E., Schneider, R., & Ferrara, A. 2003, *ApJ*, 589, 35

Schaerer, D. 2002, *A&A*, 382, 28

Schaerer, D. 2003, *A&A*, 397, 527

Schneider, R., Salvaterra, R., Ferrara, A., & Ciardi, B. 2006, *MNRAS*, 369, 825

Scoville, N., Aussel, H., Brusa, M., *et al.* 2007, *ApJS*, 172, 1

Sekiguchi, K., *et al.* 2004, *Bull. AAS*, Vol. 36, p. 1478

Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, *ApJ*, 588, 65

Shimasaku, K., Ouchi, M., Okamura, S., *et al.* 2003, *ApJ*, 586, L111

Shimasaku, K., Kashikawa, N., Doi, M., *et al.* 2006, *PASJ*, 58, 313

Stanway, E. R., Bunker, A. J., Glazebrook, K., *et al.* 2007, *MNRAS*, 376, 727

Stark, D. P., Ellis, R. S., Richard, J., *et al.* 2007, *ApJ*, 663, 10

Steidel, C. C., Adelberger, K. L., Giavalisco, M., *et al.* 1999, *ApJ*, 519, 1

Steidel, C. C., Adelberger, K. L., Shapley, A. E., *et al.* 2003, *ApJ*, 592, 728

Taniguchi, Y. 2001, in: N. Arimoto & W. Duschul (eds.), *The Japan-German Workshop on Studies of Galaxies in the Young Universe with New Generation Telescopes* (astro-ph/0301097)

Taniguchi, Y., Shioya, Y., Ajiki, M., *et al.* 2003, *JKAS*, 36, 123 (Erratum, 36, 283)

Taniguchi, Y., Ajiki, M., Nagao, T., *et al.* 2005, *PASJ*, 57, 165 (Erratum, 59, 277)

Taniguchi, Y., *et al.* 2008, *ApJ*, to be submitted

Tornatore, L., Ferrara, A., & Schneider, R. 2007, *MNRAS*, 382, 945

Tumlinson, J., Giroux, M. L., & Shull, M. 2001, *ApJ*, 550, L1

Tumlinson, J., Shull, M., & Venkatesan, A. 2002, *ApJ*, 584, 608

Tumlinson, J. & Shull, M. 2000, *ApJ*, 528, L65

Willis, J. P. & Courbin, F. 2005, *MNRAS*, 357, 1348

Willis, J. P., Courbin, F., Kneib, J. -P., & Minniti, D. 2008, *MNRAS*, 384, 1039

Yamada, S. F., Sasaki, S. S., Sumiya, R., *et al.* 2005 *PASJ*, 57, 881

Yan, H., Dickinson, M. Giavalisco, M., *et al.* 2006 *ApJ*, 651, 24

Discussion

ELDRIDGE: We (myself and Elizabeth Stanway) also have looked for He II $\lambda1640$ at high redshift. We have a stacked spectrum of 50 galaxies with a mean redshift of 4.7 and we see no He II to a quite low limit.

TANIGUCHI: Thank you for your comment.

PETTINI: In our survey of UV-bright galaxies at $z = 2 - 3$, we have examples of galaxies with stellar populations which seem very young, with ages of only a few tens of million of years. These objects may be the lower redshift analogues of your galaxies at $z = 6 - 7$ and, if they are, they are of course much easier to study spectroscopically at the lower redshifts. Somewhat surprising perhaps, even these very young galaxies have already fairly high metallicities, between 1/5 and 1/3 of solar. It seems that once star-formation starts in these kinds of high redshift galaxies, it proceeds very fast, so that the traces of the first few generations of stars are quickly swamped. Thus, you may find that it is also very difficult to catch one of your z = 6 - 7 galaxies, which are also undergoing vigorous star formation (otherwise you would not see them), at such an early stage that the signatures of Pop III stars can be discerned.

TANIGUCHI: Now, one of the most important issues in this research field is to search for galaxies with Pop III stars at high redshift. Aslthough theoretical considereations suggest that such galaxies could be found at $z > 2.5$. However, any trials made so far failed to identify such galaxies. I think that we need more systematic search for Pop III dominated galaxies at $z > 2.5$ by using a large sample of galaxies (i.e., LAEs) in near future.